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Lake Restoration by Dilution
Moses Lake, Washington

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16. ABSTRACT
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LAKE RESTORATION BY DILUTION: MOSES LAKE, WASHINGTON

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Abstract—Dilution water, low in macronutrients, was added to Moses Lake on three occasions in 1977 and once in 1978 during the spring–summer period. The addition resulted in reducing the annual average inflow concentration of phosphorus from about 130–140 $\mu g\,l^{-1}$ to 100 $\mu g\,l^{-1}$. The water exchange rate in Parker Horn, which is 8% of the lake volume, increased from about 1% day^{-1} normally to 7 and 11% day^{-1} for the May–September period in 1977 and 1978, respectively. Lake water was displaced at a predictable rate in the whole lake as well as the areas proximal to the input, as verified by specific conductance.

Improvements in lake quality, compared to values from 1969–70, were rather good with greater reductions in algal biomass occurring than might have been expected to result from the less impressive reductions in total P content. Chlorophyll *a* decreased by about 60–80% and total P decreased by about 50–60%, depending on the area of the lake. However, Chl *a* averaged only 15 $\mu g\,l^{-1}$ during May–September 1978, while total P was rather high at 70–80 $\mu g\,l^{-1}$. The fraction of the phytoplankton composed by blue-green algae decreased from 96% in 1970 to 68% in 1977–78. The cause for the effect on biomass and species composition is unknown, but may be related to dilution of blue-green excretory products.

A dilution water input of about 6 $m^3\,s^{-1}$ continuously during April–September would require 20% less total water and should provide adequate control of eutrophication in at least 30% of the lake volume proximal to the input and Parker Horn. That would provide an exchange rate of 5% day^{-1} for Parker Horn and should achieve lake water residuals by midsummer of ≤50%. Two additional inputs to the lake are also proposed as two more phases in the restoration project.

INTRODUCTION

The effects of adding low nutrient dilution water to eutrophic lakes, for the purpose of reducing their algal content, are two-fold and lead directly from the dynamics of continuous cultures. By reducing the inflow nutrient concentration the maximum biomass possible in the reactor vessel of a continuous culture is likewise reduced because the maximum possible nutrient concentration in the reactor is lowered. If on the other hand the water exchange rate is increased, nutrients and algal biomass are more rapidly washed out of the reactor preventing a biomass accumulation. Since the concentrations of nutrients and biomass are also critical variables in lakes the controlling factors in continuous cultures are often analogous to those in lakes.

The effect of inflow concentration inferred above also follows from Vollenweider's (1969) model for the steady state phosphorus (P) concentration in $\mu g\,l^{-1}$:

$$P = \frac{L}{\bar{Z}(\rho + \sigma)}$$

where L is the areal loading in mg $m^{-2}\,yr^{-1}$, $\bar{Z}$ is the mean depth in m, and ρ and σ are the coefficients for the flushing (water exchange) and sedimentation rates in yr^{-1}, respectively. Clearly if the flushing rate (ρ) can be increased proportionately more than the areal loading (L), which is the result of adding water with low nutrient concentration, then the steady state P concentration should decrease. That should theoretically reduce the potential biomass of algae in the lake. If enough water can be added so that the exchange rate approaches the growth rate of the algae, then biomass reduction can occur through washout of cells at a rate that exceeds the growth rate.

If some other growth-controlling factor (s) is present in the lake, but is absent in the dilution water, its dilution may also result in quality improvement.

Both mechanisms were thought to have potential in Moses Lake, Washington, but mainly that of a reduction in inflow nutrient concentration (Welch *et al.*, 1972). Because the bluegreen algal component (mostly *Aphanizomenon*) was found to grow at a rate of at least 0.5 day^{-1}, water exchange rates approaching that magnitude were thought to be necessary to control biomass simply by washout. However, an additional observation from bioassays performed in that study was that the growth of blue-green algae was poorer and that of diatoms better as the percent of dilution water increased. That observation suggested that some other factor besides P or N (nitrogen) concentration was controlling species composition. It was of interest, from the standpoint of food chain energy transfer as well as nuisance conditions, to determine if such a species change would occur on a large scale in the lake with the influx of Columbia River dilution water. If the growth of blue green algae could be controlled by diluting other factors than the common macronutrients then the technique would hold pro-

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mise for use in areas where large supplies of low-nutrient water were unavailable.

The restoration of Moses Lake by controlled additions of low-nutrient Columbia River water has been seriously considered since it was suggested by Sylvester & Oglesby (1964). Although funds were awarded by EPA in 1968, controlled releases of water were not actually added to the lake until thirteen years later as part of the Clean Lakes Program of EPA. The logic of using Columbia River water to improve the quality of Moses Lake has long been obvious. Facilities were in existence, but infrequently used, to divert Columbia River water, destined for irrigation use, through Moses Lake with little or no consumption. The ratio of nutrient content in Columbia River water to Moses Lake water was also highly desirable; about 1:7 and 1:18 for total P and N, respectively.

Moses Lake lies in eastern Washington and partially surrounds the city of Moses Lake, population about 11,000 (Fig. 1). The lake has an area of 2753 hectares, a volume of 153.7×10^6 m^3, a mean depth of 5.6 m and a normal flushing rate of about 2 yr^{-1}. Although naturally formed by blowing sand damming the Crab Creek channel in historic times, a dam and outlet structures resulted in increased and controlled water levels. The lake is hypereutrophic having received a P and N loading of about 2 and 19 g m^{-2} yr^{-1}, respectively, during 1969–70. Nearly one-half of the nutrient load has come from irrigation return flow, with 20% of the P from sewage effluent added to Pelican Horn north of the I-90 bridge (Welch *et al.*, 1973). Chlorophyll *a*, total P and Secchi disk averaged 45 μg l^{-1}, 156 μg l^{-1} and 0.9 m, respectively during the summers of 1969–70. In some instances and places Chl *a* reached 300 μg l^{-1}. Although fishing has been popular, the recreational potential of such a large lake located in a near desert climate was greatly reduced by its hypereutrophic state.

Dilution water has been added to Parker Horn of Moses Lake from the Eastlow Canal via Rocky Coulee Wasteway and lower Crab Creek (Fig. 1) during the spring–summer periods of 1977, 1978 and 1979. The original proposal was to add water at a rate of about 32 m^3 s^{-1} for 10 days in the spring. Based on studies with a physical hydraulic model (Nece *et al.*,

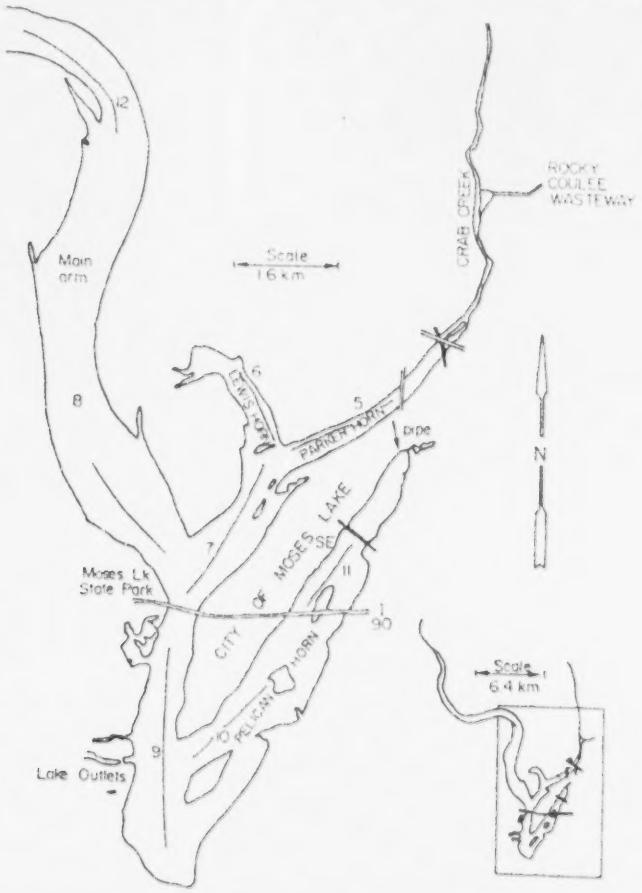

Fig. 1. Showing sampling transect locations and treated sewage effluent (SE) and pipe connecting Parker and Pelican Horns proposed in Phase II.

Table 1. Dilution water inflow rates to Parker Horn, Moses Lake via Crab Creek showing mean water exchange rates for Parker Horn and the whole lake during April–September

Dilution period	Flows in $m^3 s^{-1}$ Total	Crab Creek	Exchange rate in $days^{-1}$ Parker Horn	Whole lake
1977				
3/20–5/7	34.0	0.4		
5/22–6/4	11.8	1.3	0.11	0.009
8/14–9/18	19.8	2.5		
1978				
4/20–6/18	21.7	1.7	0.07	0.006

1976) the results from which compared closely with those using a simple continuity model, that rate of dilution water input was considered adequate to maximize the reduction of total P in Parker Horn. Depending upon the observed rate of return of lake P to pre-dilution levels, a second and possibly third 10-day application was proposed during the summer. Although water was not available in the exact quantities or at times proposed, nevertheless, U.S. Bureau of Reclamation personnel at Ephrata, Washington, have cooperated with information and generous water releases. This is considered Phase I of the restoration program proposed by Brown and Caldwell Engineers.

Phase II of the restoration involves connecting upper Pelican Horn with Parker Horn by means of a pipe and pumping facility to provide 1.5 $m^3 s^{-1}$ input continuously during the summer period. Pelican Horn contains 5% of the lake volume and at that inflow would exchange at 3.2% day^{-1}. Under that scheme water would be added continuously to Parker Horn during April through August at at rate of 5.7 $m^3 s^{-1}$, which together with Crab Creek (1.7 $m^3 s^{-1}$) would be an exchange of 5.5% day^{-1}.

Phase III involves delivering dilution water to the upper main arm (63% of volume) of the lake at a rate of about 8.6 $m^3 s^{-1}$ or a total exchange (including Rocky Ford Creek flow) of about 1% day^{-1}. Whether Phase II will be completed before Phase III or both phases proceed together is unknown at this time. Sewage effluent is scheduled for diversion from Pelican Horn in 1981, which will permit much greater improvement in quality there than would have otherwise been possible.

This paper will include results of the Phase I experiment to: (1) determine the degree of improvement in t. phic state indicators as a result of adding dilution water during 1977 and 1978 compared to prediversion data in 1969 and 1970; (2) determine if the improvement in quality was related to a reduction in the concentrations of macronutrients or another factor(s) and (3) develop an optimum dilution scheme to maintain the restored state.

TREATMENT AND ANALYSIS

Dilution water

Columbia River water was routed through Parker Horn on three occasions in 1977 and one in 1978 (Table 1). More water was added in 1977, but the spring dilution period was of greater continuous length in 1978. In order to treat the spring-summer periods as a whole, average rates of water exchange (ρ) including Crab Creek base flow plus dilution water, were calculated for April through September. Because it was found in 1978 that dilution water reached halfway through the main lake, rates of exchange were calculated also for the whole lake volume.

Overall the rates of exchange for the whole lake during the April–September periods in 1977 and 1978 (0.009 and 0.006 day^{-1}) were not that different from the annual rates for those years (0.007 and 0.006 day^{-1}) or for that matter from the 1969–70 rates (0.006 day^{-1}). The critical period of course is during late spring and summer when the exchange rate for Parker Horn is normally about 0.01 day^{-1}. Thus, the rates in Parker Horn during the summer of 1977 and 1979 were eleven and seven times greater than normal. In addition to the rate increase, quality changes were also brought about by the pristine character of Columbia River water.

Analysis of constituents

Sampling of water for the determination of total phosphorus, ortho P, nitrate nitrogen (NO_3-N), total N, chlorophyll *a* (Chl *a*) and plankton cell carbon was conducted by collecting water from a depth of about 0.4 m along seven horizontal transect sites in 1977 and 8 sites in 1978 (Fig. 1). Station 12 was added in 1978. At a midpoint of each transect, profiles of DO, pH, temperature and specific conductance were also determined as well as Secchi disk depth. Samples were also collected in the profile for the determination of nutrients in both years and Chl *a* in 1978, but were used only as general information in this analysis. The horizontal composite samples were used as primary data to compare with values from 1969–70 which were determined by similar collection techniques.

Samples were collected weekly except during the three dilution periods in 1977 when they were collected more frequently. Filtration and other sample preparations were conducted at facilities at Moses Lake, but nutrient and Chl *a* analyses were performed the following day at Seattle. Procedures for nutrient

Table 2. Water quality improvement in Moses Lake, Washington following dilution water additions in 1977–1978. Data represent May–September means from transect water collections at 0.4 m depth. Percent lake volume, percent improvement and estimated total N values represented in parentheses

	Parker Horn (8%)	Lower lake (21%)	Whole lake (58%)
Total P			
1969–70	158	156	156
1977	81 (49)	101 (35)	93 (40)
1978	61 (61)	86 (45)	76 (51)
PO_4-P			
1969–70	28	48	41
1977	30 (−7)	56 (−17)	46 (−12)
1978	13 (54)	24 (50)	15 (63)
Total N			
1969–70	(1500)	(1400)	(1200)
1977	540 (64)	620 (56)	600 (50)
1978	440 (71)	520 (63)	470 (61)
$NO_3 + NO_2$-N			
1969–70	71	23	53
1977	69 (3)	48 (−108)	48 (9)
1978	48 (32)	19 (17)	43 (19)
Chl *a*			
1969–70	71	42	45
1977	35 (51)	27 (36)	27 (40)
1978	16 (78)	15 (64)	16 (64)
Secchi depth			
1969–70	0.6	1.0	0.9
1977	1.3 (54)	1.8 (44)	1.5 (40)
1978	1.2 (50)	1.7 (41)	1.3 (31)

and Chl *a* analysis were largely those from Strickland & Parsons (1968) with the following characteristics: phosphate—ammonium molybdate heteropoly blue complex; total phosphorus—persulfate digestion; nitrate—copper cadmium reduction column; organic nitrogen—u.v. light oxidation; chlorophyll *a*—fluorometric analysis of acetone extracts.

Phytoplankton analysis involved counting cells or in the case of blue greens, unit colonies, in transect samples collected at 0.4 m. All counts were converted to cell volumes and carbon based on appropriate cell measurements and geometric configurations and carbon: volume relationships of Strathmann (1977). Most counts during 1977–78 are from station 9 with a few from statiion 7. In 1970 daily counts were made on surface samples from station 7 during four 2-week periods during the summer. Means for those four periods were converted to cell volumes and carbon. Phytoplankton data are reported as percent of phytoplankton carbon represented by blue-green algae.

Nutrient loading

Phosphorus loading was estimated as the product of total P concentration from surface and ground water inflows, sewage effluent, and precipitation and quantities of water from those respective sources. Flow records from the two major inflow streams (Crab and Rocky Fork Creeks) were obtained from the U.S. Geological Survey records and dilution water input and lake outflow were available from the U.S. Bureau of Reclamation. Precipitation and evaporation were available from the local airport and groundwater input was estimated by difference.

Loading and output of P were calculated on a monthly basis. Phosphorus determinations were available from surface inflows and the lake near the outflow on a weekly basis during spring, summer and fall and monthly during the winter. For other sources, average values for P concentration were used along with montly totals for water input.

RESULTS

Lake quality

Marked improvement resulted from dilution water in all areas of the lake except in Pelican Horn where sewage effluent enters and dilution water showed little penetration. However, improvement in lake quality was generally greater in Parker Horn (station 7) than in the lower lake (station 9) or in the whole lake, which is represented by a weighted mean for most of the lake volume (Table 2). Of particular interest as trophic state indicators are total P, Chl *a* and Secchi depth. The May to September mean values in Parker Horn showed at least ten percent more improvement, compared to 1969–70 values, than in the lower lake or whole lake. In order to compare a percent improvement for Secchi depth, reciprocals of the Secchi depth were used.

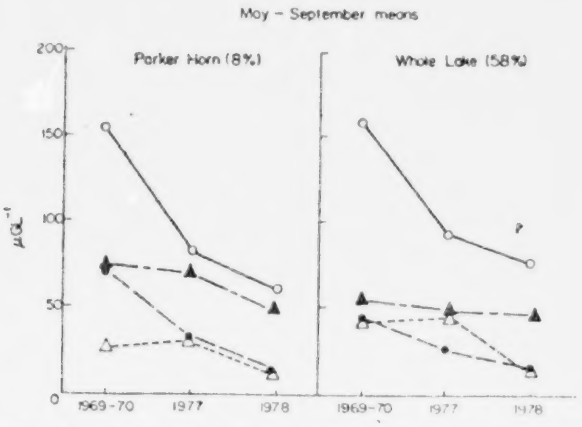

Fig. 2. Mean May–September values for nutrients and Chl *a* in Parker Horn and Moses Lake as a whole (volume weighted) before (1969, 1970) and after (1977, 1978) dilution water addition. Total P and Chl *a* are open and solid circles, respectively. Phosphate-P and nitrate-N are open and solid triangles, respectively.

Improvement in the three quality characteristics in Parker Horn was expected to exceed that in other areas simply because the dilution water entered the lake there. Exchange rates were considerably greater in Parker Horn than in the lower lake as well as being greater than in the whole lake (Table 1). However, improvements were more pronounced than expected in areas other than Parker Horn. Although the exchange rates in the whole lake (100% of volume), for the two spring–summer periods were only about 10% of the rates for Parker Horn, improvement in quality indices was nevertheless around 50%. Therefore, dilution water traveled throughout the lake and into the main arm more extensively than expected (Table 2).

Another point of significance is that Chl *a* improved the second year to a greater extent than total P. While the total P improvement was about 10% more in 1978 than in 1977, the Chl *a* improvement was 25–30% greater. Soluble N (NO_3) and especially phosphate (PO_4) were much lower in 1978 than in 1977 and may have contributed to the cause for lower Chl *a* levels in 1978. This trend can be seen in Fig. 2 where, with the exception of NO_3, nutrients and Chl *a* showed marked decreases in 1978. This was in spite of the lower amounts of dilution water added and smaller resulting rates of water exchange in 1978 compared to 1977 (Table 1).

The improvement in quality by a reduction in algal biomass (Chl *a*) and increase in water clarity (Secchi depth) was also accompanied by a reduction in the blue-green component of the phytoplankton. Blue-green algae decreased from a June–September mean of 96% of the crop in 1970 to 68% in 1977 and 1978.

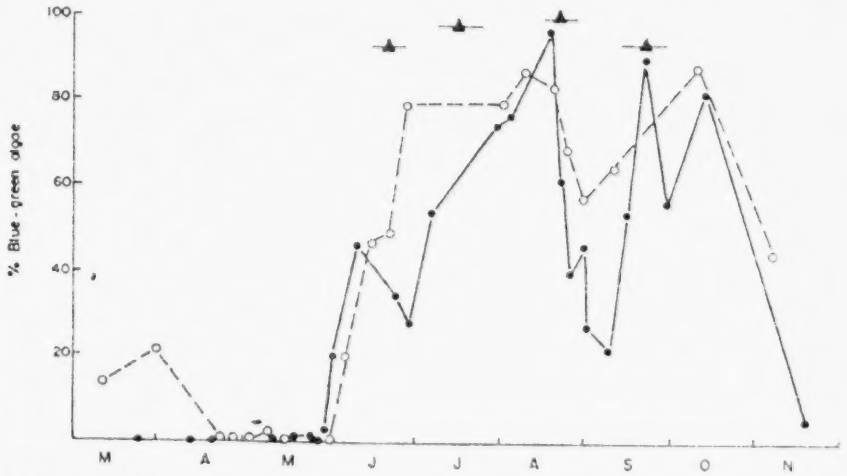

Fig. 3. Percent of phytoplankton carbon represented by blue-green algae before (1970, Parker Horn) and after (lower lake 1977–78) dilution water addition. Values for 1977 and 1978 as solid and open circles and 2-week mean values in 1970 as triangles.

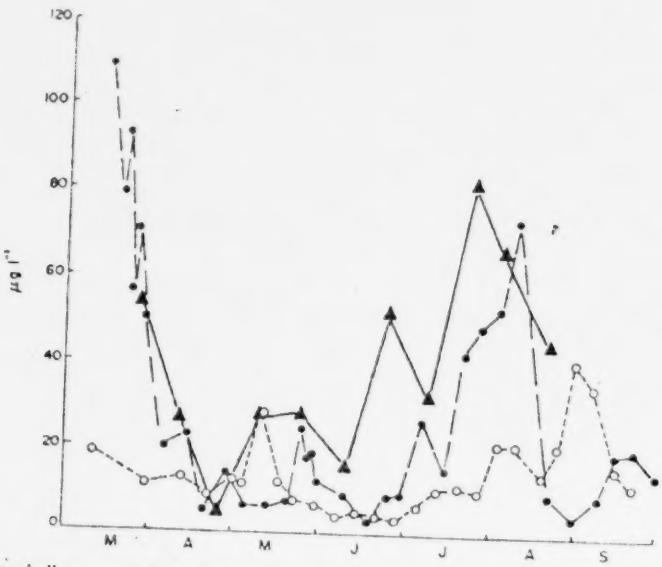

Fig. 4. Chlorophyll *a* content 0.5 m in lower section (station 9) of Moses Lake before (1969, 1970; solid triangles) and after (1977, solid circles; 1978 open circles) dilution water addition.

Figure 3 shows that although blue-greens still dominated in 1977–78 their proportion was considerably less than in 1970. The 1977–78 data in Fig. 3 are from the lower lake (station 9), and 1970 data are from Parker Horn but less frequent analyses in Parker Horn in 1978 suggests that there too blue-greens composed about two thirds of the crop.

Not only was the average Chl *a* content lower in 1977–78 than in 1969–70, but nearly all observations remained below pre-dilution values during most of the summer (Fig. 4). Further, the 1978 levels were considerably below the 1977 levels until the latter part of August when dilution water was again added in 1977 but not in 1978. One early dilution period in 1978 seemed to provide relatively lower levels of Chl *a* throughout much of the summer than did more water over three separate periods the year before. Although the dilution water effect is limited in time and once the input is terminated the algal mass is well on its way to recovery within three weeks or so, even a single dilution water input in the spring will maintain the algal mass, as well as the fraction that are blue-greens, well below levels that occur without dilution.

Phosphorus loading

Phosphorus loading was similar during the two years of dilution, differing by only about 5200 kg or 12% (Table 3). The major input is from Crab Creek, which is high in concentration because of irrigation return flows. Groundwater contributed about 30% of the water inflow but only 10% of the P because of relatively low concentrations in sampled wells. Of course, the largest contribution (40 and 30%) of water was dilution water added through Rocky Coulee wasteway and as expected the P contribution was relatively small because of the low concentration. Normally Rocky Coulee contributes about 7% of the inflow, largely through seepage from irrigation. That contribution is included with Crab Creek flow.

Annual P loading, expressed on an areal basis, was 1580 and 1390 mg m^{-2} yr^{-1} for the two dilution years, respectively (Table 4). Because the water

Table 3. Water and phosphorus budgets for Moses Lake from March 14, 1977 through March 16, 1979

Source	Water (10^6 m^3 yr^{-1}) 1977–78	1978–79	Phosphorus (kg yr^{-1}) 1977–78	1978–79
Dilution water	193.0	115.3	3702	2840
Crab Creek*	87.4	92.5	16,383	10,720
Rocky Ford Creek	52.7	58.6	9325	10,300
Sewage effluent	1.3	1.3	9539	10,053
Groundwater	126.2	123.0	4113	4036
Precipitation	6.5	4.9	515	388
Total input	467.1	395.6	43,577	38,337
Total output	439.6	370.4	29,531	29,761
Evaporation	27.5	25.2		

* Includes base flow of Rocky Coulee Wasteway as 30.5×10^6 m^3 yr^{-1}.

Table 4. Phosphorus loading characteristics for Moses Lake during 1977–78 and 1978–79. Sedimentation coefficient is calculated as the $\sqrt{\rho}$

		1977–78	1978–79
Loading, mg m^{-2} yr^{-1}	(L)	1580	1390
Retention coefficient	(R)	0.32	0.22
Mean depth	($\bar{Z}$)	5.6	5.6
Flushing rate, yr^{-1}	(ρ)	2.81	2.41
Sedimentation coefficient, yr^{-1}	(σ)	1.68	1.55
P inflow, μg l^{-1}	($\bar{P}_i$)	100	103
P lake, μg l^{-1}	($\bar{P}_l$)	76	85
P lake, calculated	($\hat{P}_l$)	63	63

exchange or flushing rate is normally about 2 yr^{-1} (and more in the dilution years) retention of P is rather low being only 20–30%. That, together with the high average P concentrations in the inflow (100 μg l^{-1}) indicate that Moses Lake was still highly enriched with P, on an annual basis, even though large quantities of dilution water were added. Without the addition of dilution water, P loadings would have been 1450 and 1290 mg m^{-2} yr^{-1} and average inflow concentrations would have been 144 and 128 μg l^{-1}.

Comparison of predicted and observed lake concentrations can give an indication of the relative significance of internal sources of P. That is, if more P appears in the lake than can be predicted by loading, washout and sedimentation, then internal sources, in this case dissolution from sediments, are probably important. The equation of Vollenweider (1969) was used for prediction of the average steady state concentration ($\hat{P}_l$), where the sedimentation coefficient (σ) is estimated by $\sqrt{\rho}$ (Larsen & Mercier, 1976). For both years $\hat{P}_l$ is 63 μg l^{-1} whereas the actual measured means were 76 and 85 μg l^{-1}. Thus, the internal P loading is apparently substantial and contributed to preventing the lake P content from decreasing to levels expected from dilution alone.

Dilution water distribution

The addition of dilution water to Parker Horn predictably and rapidly replaced lake water as judged by specific conductance measurements (Fig. 5). Per cent lake water reached values of 20, much less than in other parts of the lake, which was to be expected because the average exchange rate during the April to June dilution period was 15% day^{-1} in Parker Horn and of course decreased as more lake volume was included. As the dilution water input declined in June the per cent lake water quickly rose to between 50 and 60%.

Because Moses Lake is rather dissected and most of the volume (63%) in the main arm appears out of the path of inflow through Crab Creek (Fig. 1), dilution water was expected to have little effect other than in Parker Horn and the lower lake (station 9). However, the lake water residual decreased similarly in the lower lake as well as the entire lake. Lake water residuals reached levels between 50 and 60% in late May and early June and then began the more gradual return to normal as dilution input declined. In fact there was little difference between actual and predicted removal of lake water in the main arm and lower lake (Fig. 5). Percent residual lake water was predicted by the following equation which describes the concentration change of a conservative substance assuming complete mixing:

$$C_t = C_i + (C_0 - C_i)e^{-\sigma t}$$

where C_t, C_i and C_0 are, respectively, concentrations in μg l^{-1} at time t, in the inflow and in the lake.

DISCUSSION

The most striking results of this lake restoration project are that, (1) improvement in terms of reduced phytoplankton biomass and the levels attained as well

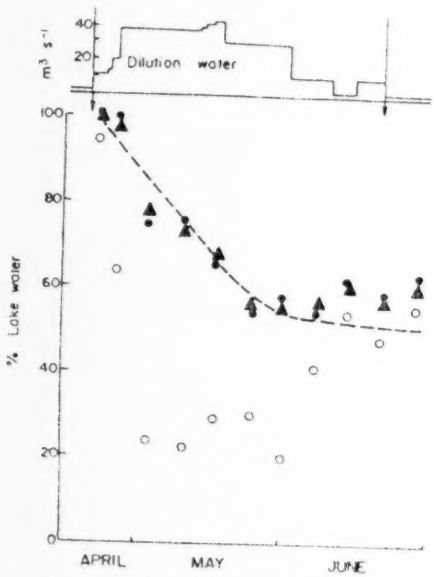

Fig. 5. Residual percent lake water in Parker Horn (station 7 open circles), the lower lake (station 9 solid circles) and the whole lake (triangles) compared to that predicted for the whole lake in response to dilution water addition in 1978. Parker Horn, the lower lake and the whole lake represent 8, 21 and 100% of the lake volume. Dotted line represents predicted values.

as increased water clarity were more impressive than were decreases in or attained levels of total P concentration, and (2) dilution water distributed more uniformly and improved lake water quality throughout the lake more than expected.

Chlorophyll *a* decreased to a May–September mean of about 15 $\mu g\,l^{-1}$ in 1978, which was a reduction of almost 80% in Parker Horn compared to 1969–70 values, and over 60% elsewhere in the lake. Total P declined as much as 50–60% below the 1969–70 values, but still remained rather high (70–90 $\mu g\,l^{-1}$). Further, blue-green algae comprised much less of the plankton crop following dilution. On an annual basis the dilution water input did not show that marked an impact on P inflow concentrations, which were around 100 $\mu g\,l^{-1}$ for the 2 years. Without dilution water, inflow concentrations of P would have been 128 and 144 $\mu g\,l^{-1}$. Thus, the striking improvements in nuisance algal levels was apparently caused by other factors than limitation by a pool of total P.

The cause for the decline in algal biomass and blue green algae fraction can not be readily ascribed to reductions in the concentrations of nutrients. Although total P declined, to some extent, in proportion to Chl *a*, it can be reasoned that both represent an index of algal biomass. Additionally, total P as a pool of limiting nutrient remained adequate to produce much more Chl *a* than observed. Although soluble levels of NO_3 and PO_4 decreased to very low levels at times in 1978, and even lower than 1977 as an average, the algal crop exposed to such low concentrations was still observed to increase. It may be that the 1978 Chl *a* levels were lower than in 1977 partly because soluble macronutrients were lower, which simply acted to slow growth rate. The algal crop in 1978 may have in fact suffered some nutritional limitations because the Chl *a*:carbon ratio was about one half that in 1977. However, a nutritional difference in the algal crop between 1977 and 1978 does not help explain the overall crop and blue green fraction decrease in the dilution years, which is nonetheless difficult to ascribe to nutrient changes.

It was argued previously (Welch *et al.* 1979) that the short term decrease of algal biomass when dilution water is added can be explained by simple washout. That explanation was based on the August 1977 dilution experience when the crop was dominated by blue-greens and Chl *a* was over 100 $\mu g\,l^{-1}$. The decrease in biomass followed an exponential curve predicted by the simple dilution equation shown above. Dispersal may explain part of that rapid decrease, but physical washout and/or dispersal can not explain the lower average biomass that has existed during the spring and summer in 1977 and 1978 as a result of dilution. Average rates of water exchange of 7 and 11% day in Parker Horn, much less rates of only 1% per day in the whole lake, are not sufficient to washout or cause dispersal when blue-green algae have been shown to grow at a rate of 50% day (Welch *et al.*, 1972).

These and other possible causes for the effect of dilution water on the biomass and composition of phytoplankton in Moses Lake will be examined in a subsequent paper. However, the most likely hypothesis at this time seems to be that dilution water inhibits the growth of blue green algae, but not diatoms. This was observed in *in situ* experiments in 1970 (Buckley, 1971; Welch *et al.*, 1972) in which diatoms increased and blue-greens decreased in response to increased fractions of dilution water. This seems to have been occurring in the lake during 1977 and 1978. Although blue-green algae remained dominant at station 9, diatoms were relatively more abundant in Parker Horn where percent lake water was less during both years. Also diatoms increased in Parker Horn in August and September, 1977, following the dilution water input and crash of blue greens. This is evident in Fig. 3 from the decreased fraction of blue greens during late August and early September of 1977. Although tentative, it seems that diatoms may be favored and blue greens discouraged once the lake fraction has been substantially reduced, probably on the order of $\geq 50\%$. This explanation conforms to some extent with that of Keating (1978), who explained the relative success of diatoms over blue greens to be a function of the degree to which allelopathic substances excreted by blue greens were diluted by flushing during the winter. If this is the principal mechanism operating in Moses Lake, rather than dilution of macronutrients, then prospects are good for use of the "dilution" technique in instances where water is available, but not of especially low macronutrient content. Further verification of that possibility must await analysis of data from 1979 including experiments with several water sources.

From the standpoint of a long-term restoration it would seem that sufficient improvement would result as long as the fraction of residual lake water approaches 50%. Dilution of lake water to fractions between 40 and 65% was attained during mid-summer in various areas of Moses Lake during 1978, along with mean Chl *a* values of about 15 $\mu g\,l^{-1}$, when the exchange rate in Parker Horn was 0.07 day^{-1}. Therefore a conservative estimate of an adequate dilution rate for Parker Horn would be ar[illegible]d 0.05 day^{-1} or a flow of dilution water of about [illegible] $m^3\,s^{-1}$. That would represent a 3:1 dilution of Crab Creek, which flows at about 1.5–2 $m^3\,s^{-1}$ in summer. Such a flow would also represent about $87 \times 10^6\,m^3$ of dilution water for the entire summer. In 1978, about $112 \times 10^6\,m^3$ of dilution water entered the lake, but over a 2-month period. Thus, slightly less total water volume spread evenly over the whole summer should provide for $\leq 50\%$ lake water remaining by midsummer throughout Parker Horn and the lower lake.

Although specifically untested, it seems that a continuous low-rate input would be preferable to a high rate input for a relatively short period, followed by

complete cessation of input. A 6 $m^3 s^{-1}$ addition should adequately reduce the fraction of lake water to $\leq 50\%$ by reducing the fraction of Crab Creek water in the inflow to $\leq 50\%$. Dilution water inputs less than 6 $m^3 s^{-1}$ that equal the flow of Crab Creek may also be adequate to produce a lake-water percent of 50 in Parker Horn and the lower lake by midsummer and should also be tested. Although this "low-inflow" procedure will not reduce the lake water fraction as quickly as the large spring input "boom and bust" approach, it may, nonetheless, more effectively restrict the large blooms of blue-greens during mid to late summer. Adding the water over a short period may reduce the lake residual to lower levels and distribute the dilution water over a larger area (though that remains to be seen), but the blue-green crop begins to increase again in about 3 weeks after the dilution water input has ceased and the lake water fraction has begun to approach a normal level.

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